SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release; Distribution Unlimited
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) UCB # 153-1200	5. MONITORING ORGANIZATION REPORT NUMBER(S) ONR Report # N00014-87-K-0396
6a. NAME OF PERFORMING ORGANIZATION University of Colorado/JILA Carl E. Wieman	6b. OFFICE SYMBOL (If applicable)
7a. NAME OF MONITORING ORGANIZATION	
6c. ADDRESS (City, State, and ZIP Code) JILA/University of Colorado Boulder, CO 80309-0440	AD-A228 539
8a. NAME OF FUNDING / SPONSORING ORGANIZATION NAVY	8b. OFFICE SYMBOL (If applicable)
9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER	
8c. ADDRESS (City, State, and ZIP Code) Office of Navel Research 800 N. Quincy Street Arlington, VA 22217	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)

Spontaneous Force Optical Traps

12. PERSONAL AUTHOR(S)

Carl E. Wieman

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 6/1/87 TO 9/30/90	October 3, 1990	13

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

We have carried out extensive studies on the use of laser light to cool and trap neutral cesium atoms. ~~We have obtained~~ high density samples of trapped cesium with temperatures as low as 0.3 mK, and ~~have studied~~ the interactions between these atoms. Because of the very low temperatures and high densities, these atoms show unique short range interactions as well as unexpected long range interactions. At short range, the laser excitation of the atoms induces inelastic collisions which lead to loss from the trap. Multiple scattering of photons leads to long range interactions between the atoms which cause the trapped cloud to behave in a collective manner, and undergo abrupt changes in shape. ~~We have also demonstrated~~ the ability to optically trap atoms directly from a low pressure vapor. ~~We have~~ demonstrated the potential of this technology for making an improved atomic clock.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

Final Report for ONR Grant #N00014-87-K-0396-P00001, "Spontaneous Force Optical Traps"

Carl E. Wieman,

Joint Institute for Laboratory Astrophysics and Physics Dept.,

University of Colorado

Abstract

We have carried out extensive studies on the use of laser light to cool and trap neutral cesium atoms. We have obtained high density samples of trapped cesium with temperatures as low as 0.3 mK, and have studied the interactions between these atoms. Because of the very low temperatures and high densities, these atoms show unique short range interactions as well as unexpected long range interactions. At short range, the laser excitation of the atoms induces inelastic collisions which lead to loss from the trap. Multiple scattering of photons leads to long range interactions between the atoms which cause the trapped cloud to behave in a collective manner, and undergo abrupt changes in shape. We have also demonstrated the ability to optically trap atoms directly from a low pressure vapor. We have demonstrated the potential of this technology for making an improved atomic clock.

a. Introduction

There has been a substantial body of work completed under this grant starting with the development of the diode laser technology needed for cooling and trapping atoms. This was followed by the first use of diode lasers for cooling and trapping atoms, the first production and study of "optical molasses" for cesium which at the time was the coldest atomic vapor ever produced, and the first demonstration of an atomic clock using laser cooled atoms. Subsequent work involved the development of a spontaneous force optical trap for cesium, and detailed studies of the behavior of the trapped atoms. These studies led to an understanding of the unique low temperature collisions which take place in such traps and their role in trap loss, and the discovery of unexpected collective behavior of the trapped atoms. Studies of this collective behavior led to the discovery of a new force between the trapped atoms which has a profound effect on the equation of state. The collisions and the collective behavior have important implications with respect to future applications of trapped atoms. In the most recent work we have demonstrated the ability to optically trap atoms in a low vapor pressure cell, and have showed that this technology could be used to make better atomic clocks. Finally we have also successfully loaded these optically captured atoms into a small magnetic trap. This work has resulted in six papers which have already been published, three major papers which are "in press", and two more papers which have been submitted. Also, one patent has been filed. There have also been more than a dozen invited talks on this work, and it has been the basis of one Ph. D. Thesis.

b. Diode laser technology development.

The great majority of the other work on laser cooling and trapping has been carried out using large expensive dye laser systems. Before this grant started we had succeeded in stopping a beam of cesium atoms using the light from a frequency chirped solid state diode laser. This work used standard commercial diode lasers which have linewidths of about 30 MHz. To obtain further linewidths. We have spent some time under this grant developing narrow linewidth laser system based on diode lasers and optical feedback. A key requirement is that it must be reliable and easy to use. We have used two designs: the first was based on locking the frequency of the laser to an external high finesse cavity following the approach of Hollberg and the second used diffraction grating feedback. Key unanswered questions regarding the first technique were: the degree of control needed for the cavity-laser spacing, the speed with which the laser frequency could be changed, and how much power must be sacrificed for the optical feedback lock. We have found that the lock can be made to work well using the light emitted from the back facet of Hitachi lasers, thus sacrificing no power from the main beam. Using the light from this facet also allowed us to make the cavity-laser spacing very small, which when combined with careful construction techniques, achieved the necessary stability in the cavity-laser separation without active feedback. This laser system gave linewidths of less than 100 kHz and with the addition of a servocontrol system based on the saturated absorption spectrum of cesium, had a long term stability of much less. We carried out a number of successful experiments using lasers of this design, and found they gave much better results for laser cooling than we had obtained with unstabilized lasers[1]. This design was also copied by groups at Stonybrook and NIST in Gaithersburg who have used it for stopping and cooling rubidium atoms.

A major component of all our work has been to develop atom trapping and cooling techniques which could be widely used. Although this diode laser system was very inexpensive, it had one flaw which made it impractical for general use. This flaw was the difficulty in initially setting the laser to the desired atomic transition, and its tendency to jump away from the desired frequency after a relatively short time. This led us to develop a new laser system. This system uses commercially available lasers which have a high reflectivity coating on the back facet and a reduced reflectivity coating on the front. These lasers are part of a laser cavity where one mirror is the back facet and the second mirror is a diffraction grating mounted on a piezoelectric transducer. After substantial development work, we have achieved a design for this system which is simple and inexpensive to make, and at the same time is very stable. With this system we still obtain the narrow linewidths required but it is now also very easy to set the laser to the desired frequency and keep it there for long periods of time. As well as being about a factor of 50 less expensive than any other tuneable laser system, this laser also meets the requirements for a general use instrument in that it is simpler and more reliable to use.

In addition to developing the general laser system design, we have also designed and built sophisticated electronic control systems for the lasers. These allow us to hold the laser frequency stable to better than a part in 10^{12}, and change laser frequencies very quickly and accurately over several hundred MHz. These capabilities have allowed us to carry out experiments which would have been extremely difficult or impossible otherwise. As a result of this work on diode lasers and their applications to laser cooling and trapping, Carl Wieman was asked to write an "invited review" on diode lasers and their applications in atomic physics which would be a special feature in *Review of Scientific Instruments*. This extensive review (89 pages) will be published in the January, 1991 edition. Although this diode laser development has not been the central focus of our work, it is clearly very important to the future applications of laser cooling. These designs provide a highly compact inexpensive and reliable laser source which consumes a fraction of a watt of electrical power. The only alternatives use 10's of kilowatts of power, cover a good sized optical table, and cost between 100 and 200 thousand dollars.

c. Optical molasses for cesium using diode lasers.

Our first activity in laser cooling under this grant was to successfully demonstrate the cooling of a cesium atomic vapor to a temperature of 100 μK.[1] At the time this work was notable in several respects. It was the only demonstration of laser cooling of a neutral atom other than sodium. It demonstrated that diode lasers could be used to cool atoms to very low temperatures and showed the advantages of optical feedback stabilization for the lasers. It was the largest sample of atoms cooled in optical molasses, and finally it was the lowest temperature atomic vapor ever produced. This work is discussed in detail in Ref. 1.

We then used these cooled atoms to demonstrate the first precision spectroscopy using laser cooled neutral atoms[3]. Specifically, we observed the cesium "clock" transition between the m = 0 states of the F =3 and F = 4 hyperfine states. To do this we first cooled the atoms in optical molasses. Then we used the lasers to optically pump all the atoms into the F =3 hyperfine ground state, and then blocked all the laser beams. During the next 20 ms of darkness a microwave field excited the clock transition. At the end of this time we excited the F =4 state with a laser. The number of scattered photons told us the number of atoms which had made a transition between hyperfine states. The linewidth we observed was better than that obtained in the 4 m long NBS-6 atomic clock, but our interaction region was only 0.5 cm long. Our linewidths were limited by the gravitational acceleration of the atoms. This experiment provided the first concrete demonstration of the advantages of laser cooled neutral atoms in atomic clocks.

d. <u>Optical trapping of cesium and low temperature collisions.</u>

Most of our work under this grant has concerned the actual trapping of cesium atoms. This is a substantial step beyond the cooling of optical molasses because it produces much higher density atomic samples, and it allows these samples to be held much longer. Following the invention of the idea of spontaneous force traps by Pritchard and Wieman[4], an MIT-Bell labs collaboration demonstrated a Zeeman shift spontaneous force optical trap (ZOT) for sodium[5]. Shortly thereafter we demonstrated a similar trap for cesium using diode lasers. This spontaneous force trap is a spectacular improvement over previous optical traps. It is nearly 100 times deeper, it has a volume about 10^8 times larger, and as a result it is able to trap far more atoms and hold them for much larger. We have been able to trap up to 4×10^8 atoms (substantially more than has been obtained with sodium), and have achieved a 1/e trapping time of more than 100 s. We have obtained densities of 10^{11}atoms/cm^3 with temperatures of 300 μK. We have studied the behavior of the trapped atoms in detail. These studies have indicated a variety of interesting and unanticipated interactions which take place between the trapped atoms. These interactions are critical in determining the number, density, and temperature of the trapped atoms. All these parameters are important in determining the usefulness of optical traps.

The first process we studied was the two body collisions between trapped atoms.[6] The earlier work in sodium[7] had shown that some sort of collisions were taking place, but they reported that the collision rate was independent of the excitation fraction. This was very surprising because a ground and an excited state atom have a strong $1/r^3$ interaction, while two ground state atoms only interact by the weaker and shorter range $1/r^6$ Van der Waals force. There was no known process which could lead to such results. In carefully evaluating this work we realized that there were many potential pitfalls in these experiments, and decided that the sodium work was probably wrong. The main experimental difficulty in such a study is that the quantity being measured is the loss rate from the trap while one varies the light intensity, but this will vary the trap depth as well as the excitation fraction. Another difficulty is that it is necessary to very accurately measure the density distribution of the atoms to relate the loss rate to a collision process. Since this loss rate is quite important for optical traps (for certain conditions it determines the density) we decided to repeat the sodium experiments more carefully. As discussed in Ref. 6, we found that in fact the sodium results were not correct, and that the loss rate did depend dramatically on the excitation rate. As shown in Fig. 1, we found that for low light intensity the collisional loss rate rose sharply if the light was decreased, while for high intensity the collisional loss rate rose proportionally with intensity. We were able to explain these results by assuming there were two types of collisions. The first was hyperfine changing collisions between two ground state atoms. The rate for such collisions can be estimated from the Langevin cross section and is quite large. However, for reasonable light intensities the trap is deep enough so that the hyperfine energy is smaller than the trap depth. When this condition is reached hyperfine changing collisions no longer cause trap loss, and the trap loss is due to radiatively induced collisions. These collisions are quite different from traditional collisions because of the very low temperature of the atoms. In a traditional collision, the collision time is much shorter than the spontaneous lifetime of the excited state. However, in this case the collision time is much longer because of the low velocities so the atoms are excited and then radiatively decay during the collision. The resulting dependence of the collision dynamics on the radiative lifetime is quite unique. We compared our experimental results with the predictions of a semiclassical model for this collision process which had been developed by Gallagher and Pritchard. We find that the model shows qualitative agreement with our results, and agrees most closely for the conditions where the semiclassical approximation is expected to work best. Thus we feel that our experiment has established the basic physics of collisional loss from optical traps, and one can, for the first, time predict what loss rates will be from different sorts of optical traps. The detailed theory of low temperature collisions is being actively pursued by numerous groups. We expect that soon these calculations will have numbers which can be quantitatively compared with our results.

d. Collective behavior of optically trapped atoms.

The collision studies were carried out with few (40,000) atoms in the trap, but we observed very dramatic and unexpected behavior when the number of atoms was increased. We will only briefly summarize the behavior here because it is too complex to be discussed in detail. Extended discussions are presented in Ref. 8 and 9. When the number of trapped atoms is less than 40,000, the cloud of trapped atoms behaves like an ideal gas in a damped harmonic potential. For larger numbers of trapped atoms the behavior is quite different however. Between 4×10^4 and about 10^8 atoms the cloud expands as more atoms are added to it and the density stays nearly constant. Above 10^8 atoms the cloud undergoes abrupt changes in its form when the number of atoms exceeds a critical value. The exact value depends on the alignment of the trapping laser beams. The subsequent forms are no longer symmetric clouds, but instead have a small central nucleus of atoms surrounded by a ring of orbiting atoms. The orbital frequency is around 100 hz, and we have studied its dependence on a variety of parameters. Under some conditions the ring of atoms is uniformly distributed, while for others it is composed of a single large clump of atoms which rotates around the nucleus. The transitions between different forms show pronounced hysteresis and bistability. We have studied the different forms and the transitions between them in detail.

We developed a theory to explain much of this remarkable behavior based on long range interactions between atoms due to their absorption and multiple scattering of the trapping light. The absorption leads to an attractive $1/r^2$ force between two trapped atoms, while the multiple scattering gives a repulsive $1/r^2$ interaction. Although these forces are weak by conventional standards, and in fact have never been observed before, they become the dominant interactions for our trapped atom samples. This is because these samples have such large numbers of very low temperature atoms. The relative sizes of these two forces depends very sensitively on the frequency redistribution of the light when it is absorbed and reemitted by an atom. When we calculate this redistribution we find the photon scattering causes a net repulsive force between the atoms. When we include this force in an equation of state of the trapped atoms we are able to get good agreement between this theory and most of our observations. Our calculations match the observed relationship between number and volume in the cloud, and predict the existence of orbiting modes with the proper frequency and size. As well as being a fascinating physics problem in itself, it is important to understand these forces because they limit the density and the number of trapped atoms we can obtain. We have not been able to explain the transition dynamics, but we are optimistic that the publication of our work will attract the interest of theorists involved with nonlinear dynamics to this unusual system.

e. Cell trap.

In the course of this work we discovered that our ZOT was sufficiently deep that it could catch atoms from the uncooled cesium beam. This led us to construct a small glass vapor cell and attempt to trap atoms directly from the low pressure vapor (10^{-7} to 10^{-8} torr). This was done by building our trap as before, with 6 laser beams intersecting at the center of the vapor cell, which had a small pair of antiHelmholtz coil around it. About 1 atom in 10^4 is moving slowly enough to be caught in the trap. This seems like a small fraction until one realizes that an atom in the cell will pass through the trap nearly 10^4 times per second, and once caught, will be held in the trap for a second or more. This results in a small cloud containing several x 10^7 trapped atoms at a density of about $10^{11}/cm^3$. The temperature of the trapped atoms is less than 1 mK above absolute zero. This provides a remarkably simple method to produce substantial samples of very cold dense atoms. It is very insensitive to laser beam quality, alignment, magnetic field, or cesium density. By switching off the magnetic field and leaving the laser light on for cooling we have produced samples which are "postcooled" to the 10 μK range, although precise measurements are difficult at this temperature. Among the potential uses of this sample are atomic resonance line filters and for atomic clocks. As a filter it is unique because the Doppler broadening is negligible so the linewidth is only the natural linewidth. At the same time the optical thickness is very high, about 50 for the cesium resonance line. We are presently pursuing the demonstration of this device for a small portable atomic clock. We have demonstrated its capabilities by observing the cesium clock transition. This is done by turning off the laser light and dropping the postcooled samples. We then drive the clock transition as they fall, and use laser florescence to detect the clock transitions.

All of this takes place in the same small cell. In this manner we have observed 7 Hz linewidths (roughly 100 times narrower than that obtained in commercial clocks) using only a 4 cm high cell. A resonance curve from this "clock" is shown in Fig. 2. There are many other factors which we have not addressed which are important in obtaining good long term accuracies and much more development work will be needed. However, it should be noted that this clock does have a number of advantages which are desirable for long term accuracy, relative to present day clocks. In addition to the narrow linewidth, these are: the interaction volume is very small, and thus can be shielded better against stray magnetic fields, and the atomic velocities are very slow which minimizes velocity dependent phase shifts. This clock is presently in the middle of the patent process and two companies, including HP, are already considering licencing agreements.

In other work with the cell trap we have been able to load the optically trapped samples into a magnetic field trap where the confining force is just provided by the interaction of the magnetic moment of the atom with an inhomogeneous magnetic field. This allows the atoms to kept cold and confined even with the laser light turned off. This is desireable for a number of potential applications of trapped atoms. These atoms are much colder than any other magnetically trapped samples, and this magnetic trap is vastly smaller and simpler than any other because the fields required are much smaller.

References

1. D. Sesko, C. G. Fan, and C. Wieman, *J. Opt. Soc. Am. B*, 5, 1225 (1988).
2. C. Wieman, L. Hollberg, to be published *Rev. Sci. Inst.*, Jan. 1991
3. D. W. Sesko and C. Wieman, *Opt. Lett.* 14, 269 (1989).
4. D. E. Pritchard, E. L. Raab, V. Bagnato, R. N. Watts and C. E. Wieman, *Phys. Rev. Lett.* 57, 310 (1986).
5. E. L. Rabb, M. G. Prentiss, A.E. Cable, S. Chu and D. E. Pritchard, *Phys. Rev. Lett.* 59, 2631 (1987).
6. D. Sesko, T. Walker, C. Monroe, A. Gallagher, and C. Wieman, *Phys. Rev. Lett.* 63, 961 (1989); T. G. Walker, D. W. Sesko, C. Monroe and C. E. Wieman, in Proceedings, Sixteenth International Conference on the Physics of Electronic and Atomic Collisions (A. Dalgarno, Ed., in press).
7. M. Prentiss, A. Cable, J. E. Bjorkholm, S. Chu, E. Raab and D. Pritchard, *Opt. Lett.* 13, 452 (1988).
8. T. Walker, D. Sesko and C. Wieman, *Phys. Rev. Lett.* 64, 408 (1990).
9. D. W. Sesko, T. G. Walker and C. E. Wieman, *J. Opt. Soc. B* (submitted).

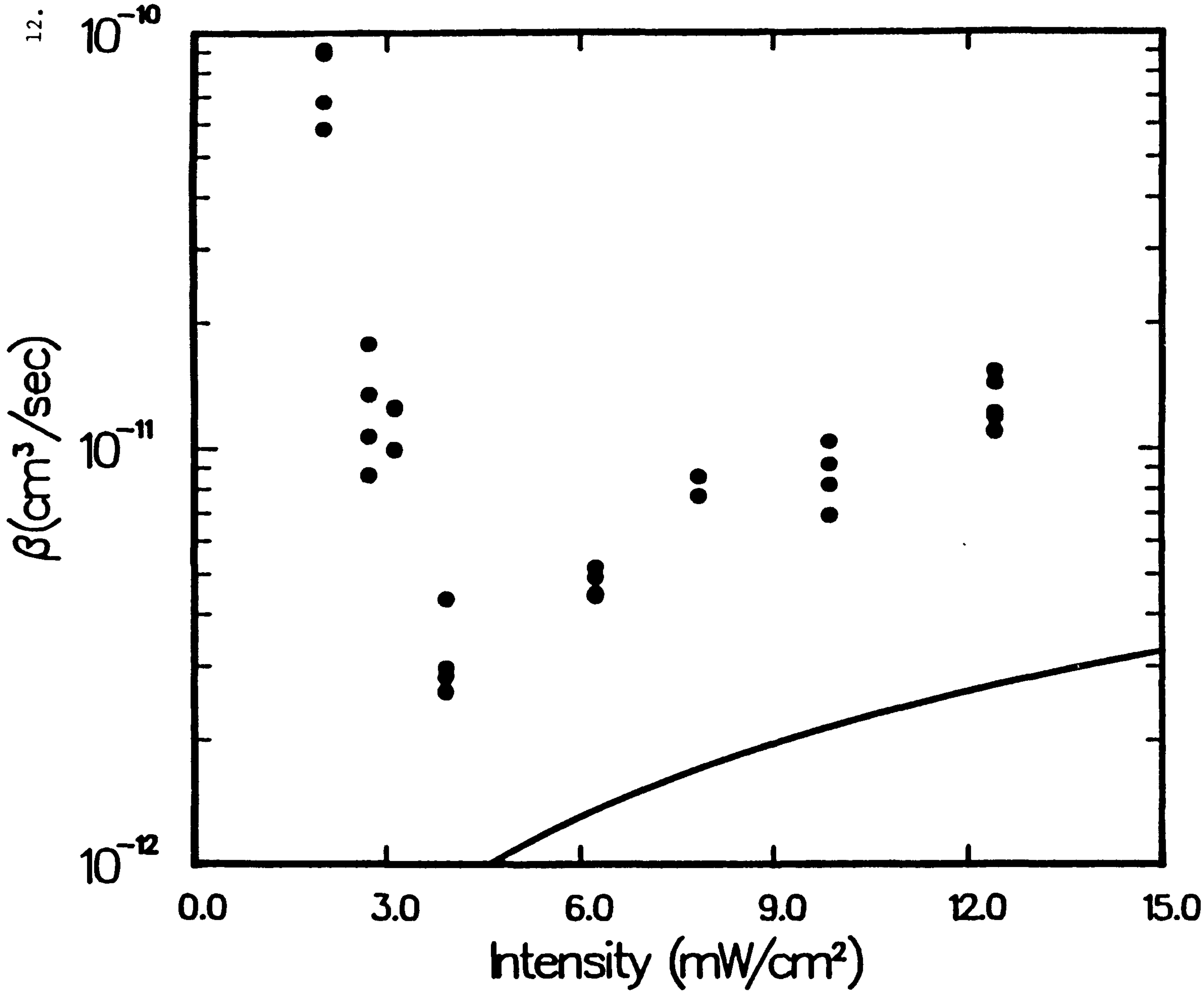

Figure 1. Dependence of collisional loss rate coefficient, β, on trap light intensity.

Figure 2. Ramsey resonance curve for cesium clock transition observed by dropping atoms from a vapor cell optical trap.